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NONCONTACT LASER GENERATION AND DETECTION OF LAMB WAVES IN PAPER

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ABSTRACT

Laser ultrasonics techniques were used to characterize noninvasively the propagation of ultrasound in paper. Ultrasonic pulses were generated using a Nd:YAG pulsed laser. An Argon-ion CW laser was used in combination with two interferometric systems to probe out-of-plane and in-plane surface motion of elastic waves. Two simultaneous propagation modes, a fast mode and a slow mode, were observed with substantially different velocities, amplitudes, and frequency contents. They were identified as the fundamental dilatational and bending modes for Lamb waves, respectively. Velocity measurements gathered from the dilatational mode along machine and cross machine directions were found to be in very good agreement with velocities obtained using in-plane contact bimorph transducers. An interpretation of the propagation modes is presented. Results are reported for various paper grades.

INTRODUCTION

The development of instrumentation for on-machine monitoring of paper structural properties has received considerable interest during the past 20 years [1-15]. This is because these properties are critical to the papermaking process, converting operations, and end-use performance of paper. It is anticipated that the availability of on-machine sensors would enable the implementation of real-time control strategies based on structural properties rather than volumetric parameters (thickness and grammage), as is presently the case. Among expected benefits would be an optimized use of raw materials (less virgin pulp and/or better use of recycled fibers to achieve targeted strength), optimization of product quality, and reduction of energy consumption (e.g., less refining and/or reduced repulping/remanufacturing).

Since it is known that empirical relationships exist between paper strength and stiffness properties [10,16], it is generally agreed that on-machine monitoring of paper strength is best achieved by testing elastic stiffness properties. In that regard, two approaches have received considerable support. The first one involves the use of a mechanical sensor in contact with the moving web and aimed at measuring the force required to distort paper in a controlled manner [11]. The second method relies on the use of contact ultrasonic transducers to infer specific stiffness from the velocity of dilatational Lamb waves in the traveling web. Various prototype implementations of the second method using rotating wheels [6-9] or sliding transducers [15] have been tested. Also, one accounts a test method using a friction-induced noise generator for excitation and a contactless microphone for detection [5].

While it is worth pursuing the development of the above techniques because they offer robustness, full consideration must be given to the development of contactless technologies. Apart from the fact that physical damage to the web would no longer be a latent issue, it would be possible to monitor a greater range of paper grades, including boards, fine papers, and tissues.

One very promising contactless approach is the use of lasers to induce and detect ultrasound in paper. The discipline is best known as laser ultrasonics [17]. Referring to Fig. 1, when laser light is absorbed by a medium, it produces localized heating and thermal expansion. If the laser intensity is time-varying (either by modulation of a CW laser or by short laser pulses), thermoelastic properties of the medium lead to the formation of elastic waves that are launched in the medium from the point of illumination.

Bending waves propagating in paper have been investigated using a ruby laser-based holographic technique [18]. Holograms were recorded on a photographic film. A Michelson interferometer was used to reconstruct out-of-plane displacements, and a CCD camera was used for visualization. This method is capable of visualizing defects such as thickness, stiffness, or density variations. Three patents related to the use of lasers for elastic wave generation in paper have been issued [19-21]. In the patent by Leugers [19], a Nd:YAG laser is used for ultrasound generation; elastic waves are detected by means of a piezoelectric transducer in contact with paper. Recordings of received pulses are reported for high density polyethylene, and numerical results are presented for various paper grades in the machine direction. These results are shown to correlate with measurements obtained using piezoelectric transducer induction. The second patent, by Pace and Salama [20], concerns the use of a nitrogen laser directed onto one planar surface of a sheet of paper and aimed at generating elastic waves propagating in the thickness direction; a piezoelectric transducer placed in contact with the opposite surface is used for detection. Laser- and contact transducer-induced numerical results are shown to agree for selected paper grades. The third patent, by Keyes and Thompson [21], considers the use of a CO_2 laser for in-plane excitation and the use of a deflectometer technique employing a HeNe laser for detection; there is no indication of measurements. Although the above patents are instructive, they do not provide details about propagation modes. Moreover, none of them relies on laser interferometry for detection.

This paper reports on the description of a laser ultrasonics technique to generate and detect Lamb waves in paper. More particularly, the method was used to detect dilatational and bending modes. Velocity measurements from the dilatational mode are of particular interest because they can be used to assess in an unambiguous manner longitudinal specific stiffness properties of paper. Following a brief review of Lamb wave propagation in paper, the experimental procedure is described. Results are next presented for various paper grades. This is completed by a discussion. A detailed account of laser generation of Lamb waves in copy paper was reported elsewhere [22].

LAMB WAVE PROPAGATION IN PAPER

As a first approximation, machine-made paper can be considered as an orthotropic material, i.e., a material in which properties are the same in a particular direction but different from properties in all directions perpendicular to that direction. In this interpretation, it is assumed that paper properties do not vary in the thickness direction (ZD). In reality, this is very unlikely because the papermaking process lends itself toward varying properties along ZD. Nevertheless, the assumption of orthotropy is satisfactory because paper is a thin material. Orthotropy implies that nine elastic stiffness constants are required to describe the elastic behavior of paper. Since the propagation of elastic waves in a medium strongly depends upon stiffness properties, a full account of the medium's elastic behavior can be inferred from the testing of various propagation modes. Using special dry-contact coupling techniques, all nine paper stiffnesses for machine-made paper have been measured [23].

Assuming that paper is sufficiently thin to be considered as a plate, i.e, a medium for which surface waves can no longer propagate because their wavelength is much larger than the plate thickness, the propagation of plate waves can be considered [1, 23-26]. Plate waves, also called Lamb waves, are elastic waves with the particle oscillation perpendicular to the surface. They can be of two types: dilatational or symmetric wave and bending or asymmetric wave. Fig. 2 illustrates symmetric and asymmetric zeroth (fundamental) and first order modes for Lamb waves; higher order modes also exist, but are not shown. Symmetric and asymmetric modes imply in-plane and out-of-plane surface motion, respectively.

Typical machine direction Lamb wave dispersion curves computed using elastic stiffness constants C_{11}, C_{33}, C_{55}, and C_{13} for a 42-lb linerboard (see Table I for numerical values) are shown in Fig. 3. It is seen that the fundamental asymmetric mode, A_0, is nondispersive, i.e., frequency independent, except at low frequencies. The fundamental symmetric mode, S_0, is nondispersive up to a cut-off frequency. The first-order symmetric mode, S_1, is also non-dispersive but past the cut-off frequency. By measuring the phase velocity and frequency of Lamb waves propagating in paper, we can determine which of the possible modes are detected. We may then, in turn, use the velocity of each mode to predict the values of the elastic stiffness constants of the sample. For example, it is known that approximated values of the specific stiffnesses C_{11}/ρ and C_{22}/ρ are obtained by measuring the low frequency limit of the S_0 mode phase velocity in the machine direction (MD) and cross machine direction (CD), respectively, i.e. [23],

$$\frac{C_{11}}{\rho} = v^2_{S_0 MD} \tag{1}$$

$$\frac{C_{22}}{\rho} = v^2_{S_0 CD} \tag{2}$$

where $v^2_{S_0 MD}$ and $v^2_{S_0 CD}$ are the square of the S_0 mode velocities along MD and CD at the low frequency limit, and ρ is the apparent density. A more formal but practically tedious testing of C_{11}/ρ and C_{22}/ρ requires the propagation of bulk waves in paper stacks [23-26].

EXPERIMENTAL PROCEDURE

Test Apparatus

Observation of Lamb wave propagation in paper was accomplished by using laser ultrasonics equipment available at the Georgia Institute of Technology. A single-source configuration and two detection configurations for out-of-plane and in-plane motion were used. The source laser was a pulsed Nd:YAG laser operating at 1064 nm with an energy output of 5.7 mJ over 10 ns and a repetition rate of 10 Hz. The laser was focused down to a spot size of 70 μm on the target using a focusing lens. A 2-watt CW Ar:ion laser operating at 514.5 nm was used for detection. Schematic diagrams for out-of-plane detection and in-plane detection systems are shown in Figs. 3 and 4, respectively. These systems, based upon heterodyne interferometry [17], are typically used for testing various materials other than paper or wood products. They were slightly adapted for the purpose of this study. They are now briefly reviewed.

Description of the out-of-plane system is as follows. Referring to Fig. 3, the linear polarized Ar:ion laser enters a 40-MHz Bragg cell that splits the laser into a detection beam (D) that is frequency shifted by 40 MHz, and a reference beam (R). The detection beam is steered perpendicular to the surface of the sample and focused onto a 5-10 μm-spot size with a microscope objective lens. A portion of the beam is scattered back off the sample and is recombined with the reference beam, thus producing an interference pattern that is then collected by an avalanche photodetector. The recombined beam contains a 40 MHz-beat frequency due to the Bragg cell frequency shift of the detection beam. The signal from the photodetector is run through an FM discriminator that is set to zero output at 40 MHz. Any further frequency shifting of the detection beam due to motion of the sample under the detection spot (i.e., from Lamb waves passing by) then appears as slight changes in the 40 MHz-beat. These changes are registered as such by the FM discriminator. These changes are proportional to the instantaneous surface velocity of the sample, and are integrated to determine the position of the sample as a function of time. The out-of-plane detection system is very sensitive to motions perpendicular to the sample surface, while motions parallel to the surface are undetected.

The in-plane motion detection system is shown in Fig 4. Upon exiting the Bragg cell, the reference beam (R) and frequency shifted detection beam (D) are steered around and focused at the same spot on the sample so that they illuminate the paper at a 45-degree angle to the surface and 180 degrees apart longitudinally (where the z-axis is perpendicular to the sample surface).

The spot size is approximately 50 μm. These beams scatter off the sample surface and are collected by a microscope objective lens directly above and perpendicular to the impact spot. The interference pattern is collected by an avalanche photodetector. A beat frequency similar to that described above for the out-of-plane detection system is in the collected beam and is processed similar to the out-of-plane signal. Due to the geometry of this detection system, it is sensitive to motions parallel to the surface, but displacements perpendicular to the surface are canceled out.

Sample Preparation and Characterization

Samples with an area of 12.5 x 12.5 cm^2 were prepared from seven different commercial grades of paper. Together, they covered a large segment of paper production. Characterization was performed in a controlled environment at 23°C and 50% RH, except for laser ultrasonics tests, which could not be made at controlled temperature and relative humidity for practical reasons (typical conditions were around 20-25°C and 20-50% RH). Grammage and soft-platen thickness for selected samples are shown in Table II. No attempt was made to gather information about the fiber network structure, type of furnish, fiber dimensions, or additives. Using a routine testing procedure involving a pair of polarized contact bimorph transducers resonating at 80 kHz [27], longitudinal velocity measurements (S_0 mode) were obtained in the machine and cross machine directions of the samples. These measurements served as a basis for comparison.

Laser Ultrasonics Testing

During a test, a sample was mounted in an aluminum frame. The source and detection systems were aligned and set at a known separation distance. Alignment was either along machine direction or cross machine direction. The Nd:YAG laser was fired and the detection system (either out-of-plane or in-plane) recorded the ultrasonic pulses produced. The source beam power density and diameter were adjusted in such a way as to maximize signal strength while avoiding damage to the sample. Damage assessment was evaluated using an optical microscope.

Typical data collection runs involved averaging shots at the same source/detector locations, then changing the separation distance between the source and detection spots and running again. The number of repetitions (shots) was not the same for all samples or separation distances: with a typical average of 10, it was increased or decreased depending upon signal strength for a particular paper grade. For the out-of-plane detection system, the source and detection spots were initially separated by 3.50 cm, and then decreased by 0.30 cm using a micrometer actuator translational stage for each successive run. Similarly, for the in-plane system, the source and detection spots were initially 1.50 cm apart, and then decreased by 0.20 cm for each successive run. Physical restrictions did not allow observations when the separation distance was less than 0.20 cm. All samples were tested with both the out-of-plane and in-plane detection systems.

Recorded signals were run through a software bandpass filter (50 kHz to 5 MHz) to help remove noise. A cross-correlation technique was used to determine the time delay, Δt, between two signals obtained for two different separation distances. In order to enhance time resolution, a second-order polynomial fitting procedure was applied to the maximum peak of the correlation function [12]. The cross-correlation/fitting procedure combination yielded results with a time resolution of approximately ±5 ns. Using the change in separation distance, Δd, between the two waveforms, it was straigthforward to compute the velocity of Lamb waves, i.e., $v = \Delta d / \Delta t$.

RESULTS AND DISCUSSION

Figs. 6 and 7 show typical normalized recordings as obtained for copy paper using the out-of-plane and in-plane detection systems, respectively; the source-detector separation distance is 2.00 cm. A closer look at these figures indicates that three features can be identified. The first one is a noise pulse that is caused by electromagnetic interference generated during the firing of the Nd:YAG laser. This pulse is not real ultrasonic data and should be ignored. On the trailing edge of the noise pulse is a fast wave signal. Further away in time is a slow wave signal. Amplitudes of these signals are somewhat inverted when in-plane detection is considered. It was not possible with the existing setup to eliminate the Nd:YAG noise pulse, which was shown to interfer with the fast wave signal for some of the observations. Also, this ruled out any successful attempt to detect elastic waves propagating in the thickness direction of paper with the current setup. One should note that the signal-to-noise ratio for both slow and fast wave signals can be significantly improved when laser-generation parameters are optimized [22].

The slow wave corresponds to the fundamental bending mode (A_0) for Lamb waves. The fast wave is identified as the fundamental dilatational mode (S_0) because velocities for this propagation mode were found to agree very well with velocities gathered using contact transducers (see below). Since the A_0 and S_0 modes were detected using both detection systems, it appears that neither mode is pure. For example, the S_0 mode has a small out-of-plane motion component.

As mentioned earlier, the source beam has a spot size of 70 μm, i.e., approximately twice as large as the typical average fiber diameter for wood pulp fibers. This means that thermal coupling overlaps more than one fiber but may still be susceptible to small-scale formation fluctuations. Indeed, signal strength was seen to vary by simply translating the sample with respect to the source beam position. However, and most importantly, there was no evidence that the velocity measurements were sensitive to the coupling efficiency. This would support that averaging takes place in the fiber network during propagation from the source to detection positions.

Although not systematically performed due to unsatisfactory signal-to-noise ratio for some of the observations, an analysis of the S_0 mode wavelength as obtained from the ratio of the velocity to peak signal frequency revealed that the magnitude of the wavelength was comparable to fiber dimensions (millimeter range). It is hypothesized that the S_0 mode frequency may be driven by fiber dimensions.

Since the A_0 mode is not observed using contact bimorph transducers, and as such remains to be investigated, the attention focused on velocity measurements obtained using the S_0 mode. Comparison was made with contact velocity measurements. Machine and cross machine direction results are displayed in a graphical form in Fig. 8 for all samples. The solid line represents a linear regression with a regression coefficient of 0.98, indicating an excellent correlation between the two data sets. Reported laser ultrasonics measurements are average values of at least three results. Based upon the confidence intervals, one can conclude that the measurements are very repeatable. Repeatability could further be enhanced by not varying the source-detector separation distance as it was the case in this work. Also, optimization of generation and detection conditions could significantly improve data quality. It should be noted that the average measuring length using laser ultrasonics is approximately 2 cm, i.e. less than the 7 cm measuring length used with contact transducers.

CONCLUSIONS

The use of a laser ultrasonics technique for the determination of Lamb wave propagation in paper has been demonstrated. A source laser and two interferometric detection systems for out-of-plane and in-plane surface motions were used to observe the A_0 and S_0 modes for various paper grades. It was shown that the laser ultrasonics velocity measurements for the S_0 mode are in good agreement with routine contact velocity measurements for machine and cross machine directions.

Additional work is required to improve our understanding of laser-induced Lamb waves in paper. Since the technique is nondestructive and can provide real-time data, its adaptation for on-machine specific stiffness testing along MD, CD, or other in-plane directions, can be envisioned.

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Table I Typical measured elastic stiffness constants for a 42-lb linerboard. C_{13} and C_{23} are estimates. See Table II for grammage and soft-platen thickness values.

C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}	C_{12}	C_{13}	C_{23}
GPa	GPa	GPa	GPa	GPa	GPa	GPa	GPa	GPa
10.3	2.94	0.057	0.126	0.174	1.93	0.917	0.1	0.1

Table II Selected paper grades and basic properties.

Sample	Grammage	Soft-platen Thickness
	(g/m^2)	**(μm)**
Printing Paper	40.2	54
Newsprint	47.8	74
Copy Paper	77.0	96
Sack Paper	81.4	113
Medium	157.4	231
42-lb Linerboard	211.1	299
69-lb Linerboard	314.7	410

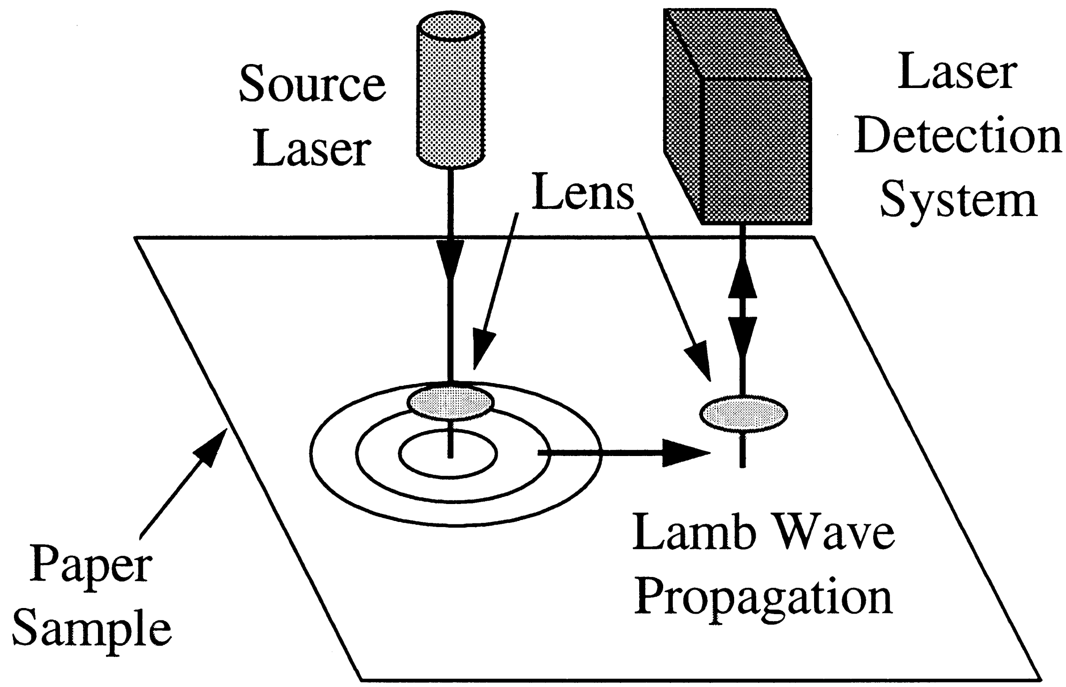

Fig. 1. Schematic diagram of laser ultrasonics generation and detection principles.

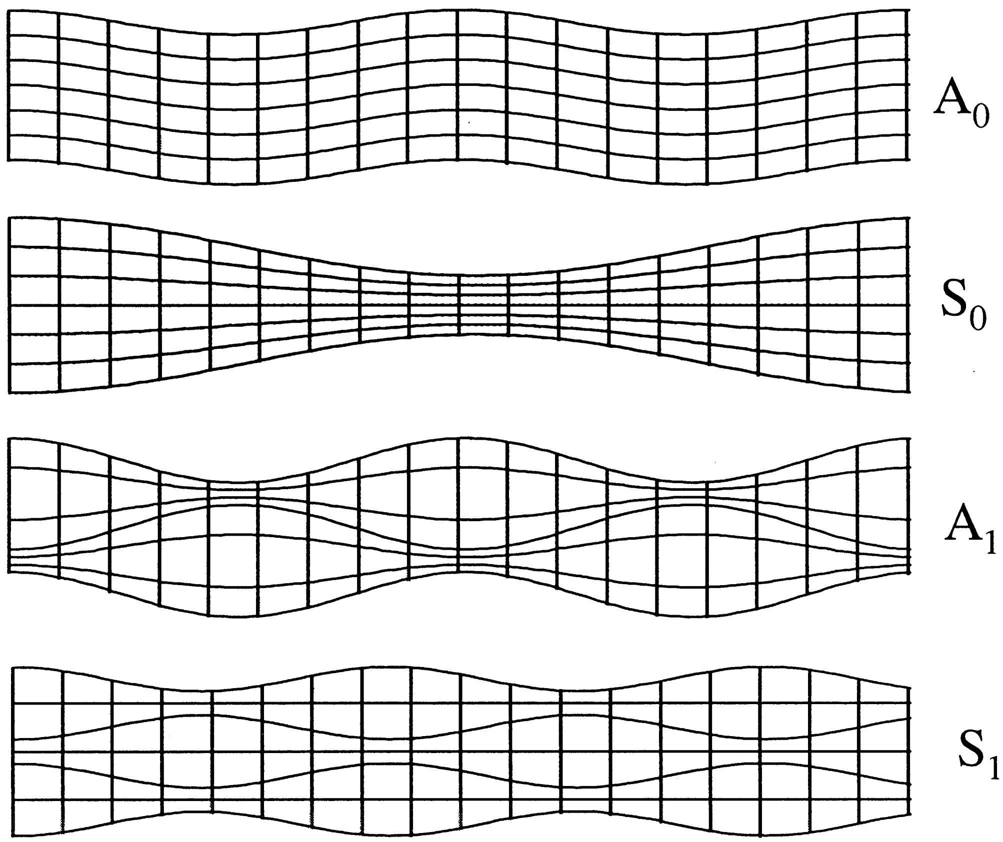

Fig. 2. Symmetric (S_n) and asymmetric (A_n) propagation modes for Lamb waves. From top to bottom: A_0, S_0, A_1, S_1. Note that these plots are only for specific places on each propagation mode curve (See Fig. 3). Moving along the propagation mode curve changes the frequency of the plot and may cause subtle changes to the actual mode shape.

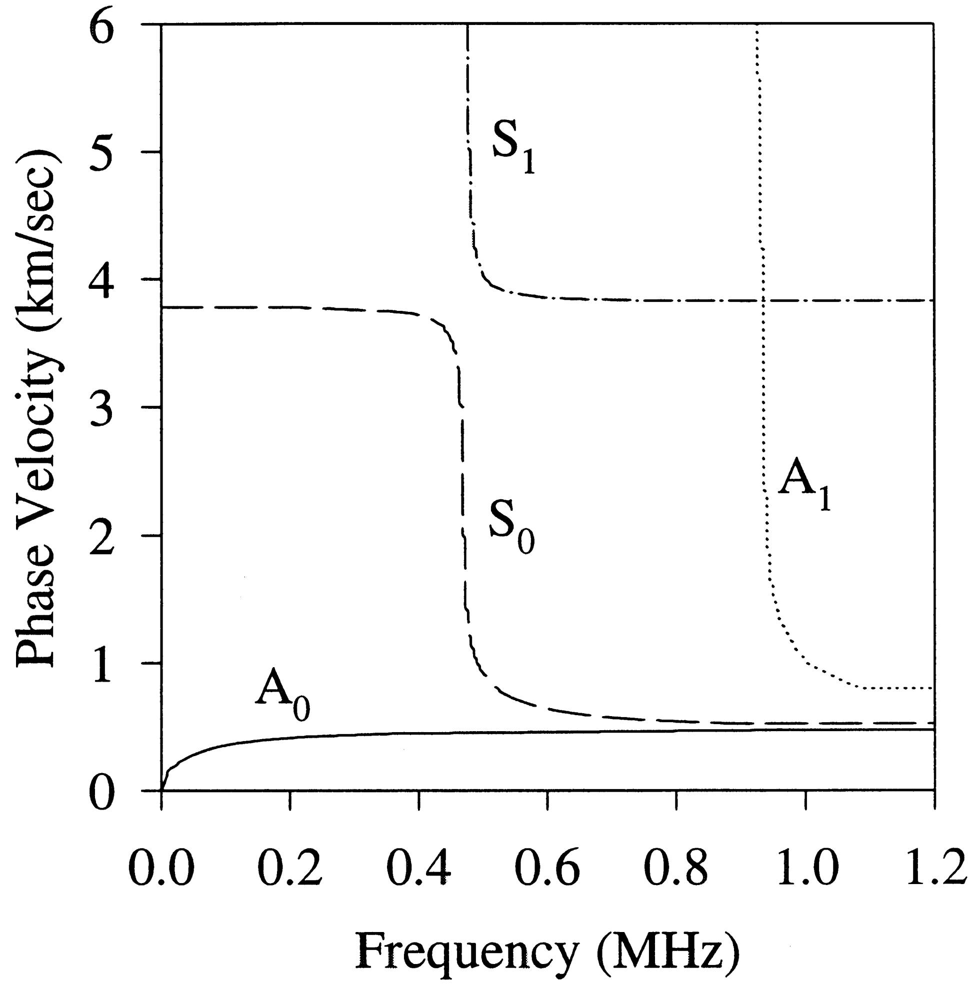

Fig. 3. Machine direction dispersion curves for Lamb waves propagating in a 42-lb linerboard.

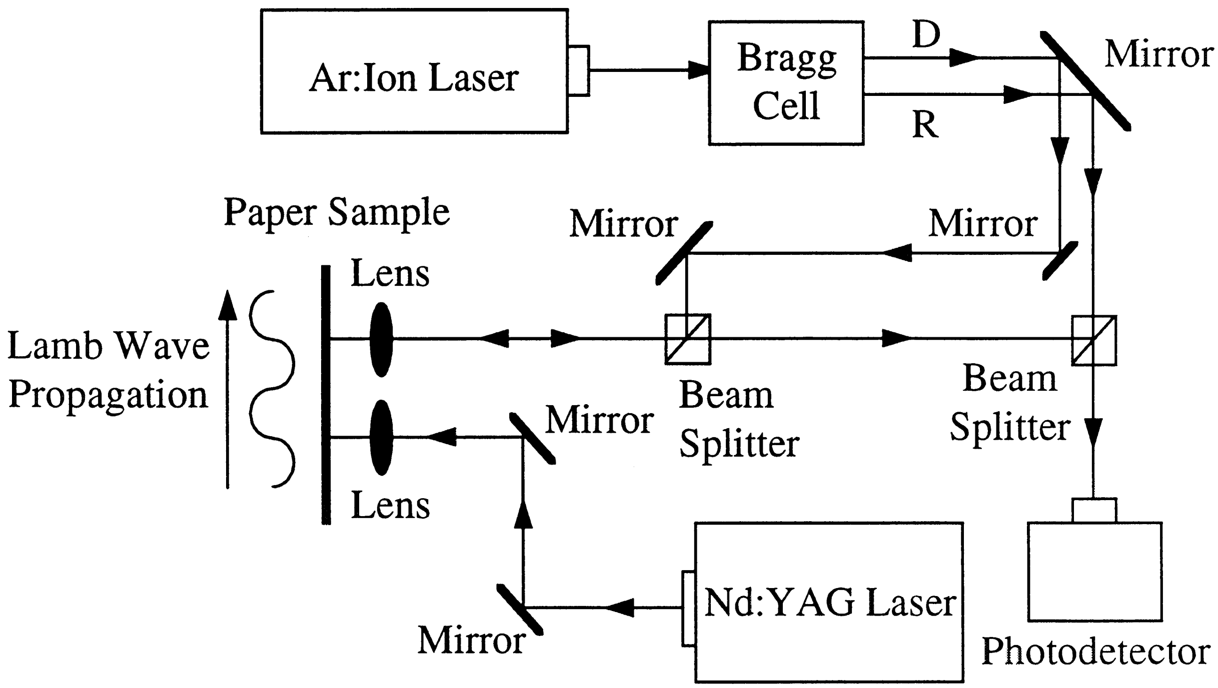

Fig. 4. Schematic of the out-of-plane motion detection system. Exiting the Bragg Cell, "R" refers to the Reference beam, and "D" refers to the Detection beam.

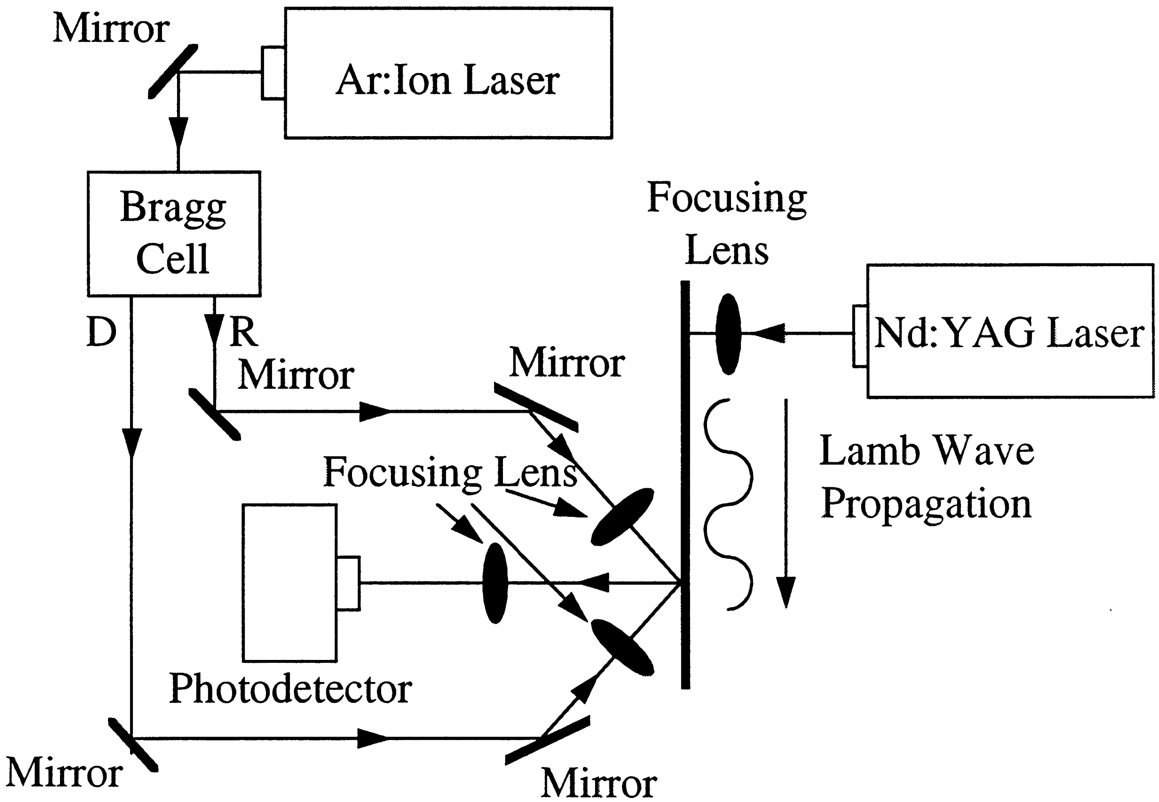

Fig. 5. Schematic of the in-plane motion detection system. Exiting the Bragg Cell, "R" refers to the Reference beam, and "D" refers to the Detection beam.

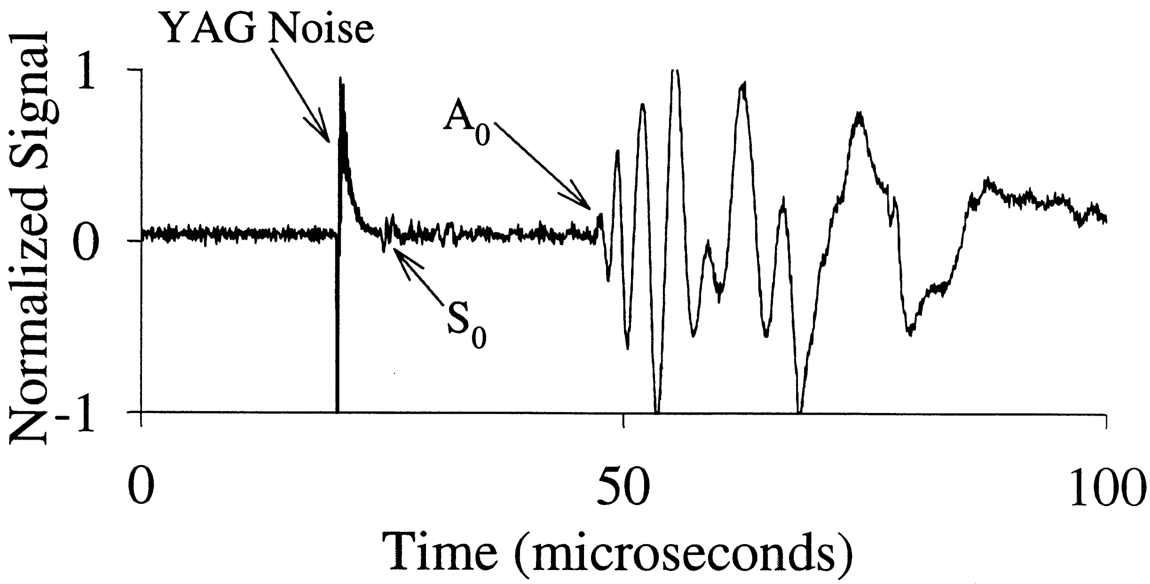

Fig. 6. Lamb waves detected in copy paper using the out-of-plane motion detection system.

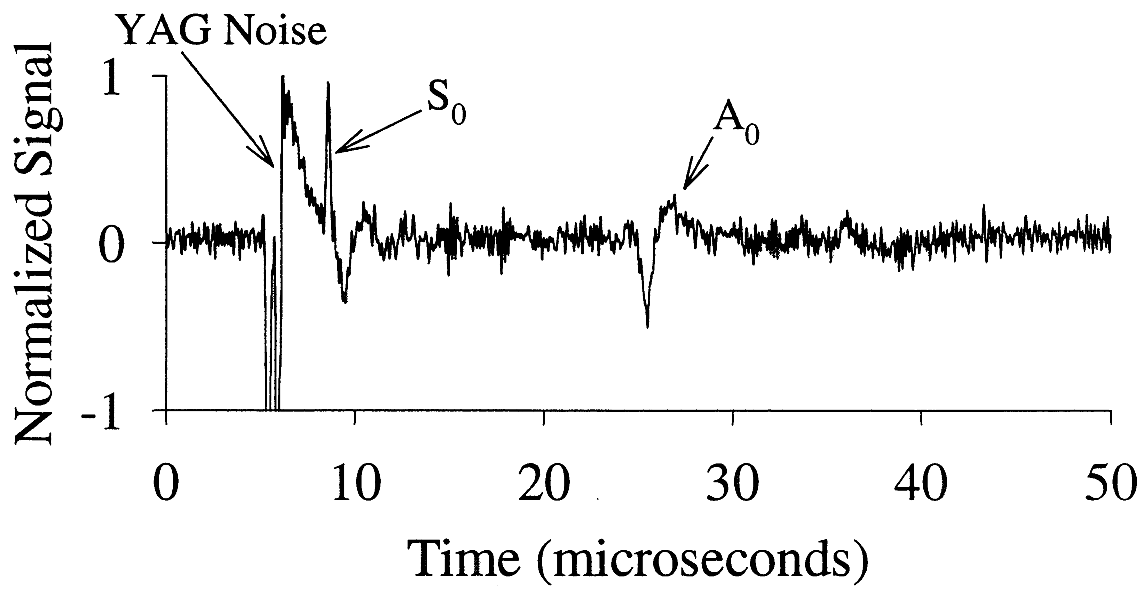

Fig. 7. Recording of Lamb waves in copy paper as obtained using the in-plane motion detection system.

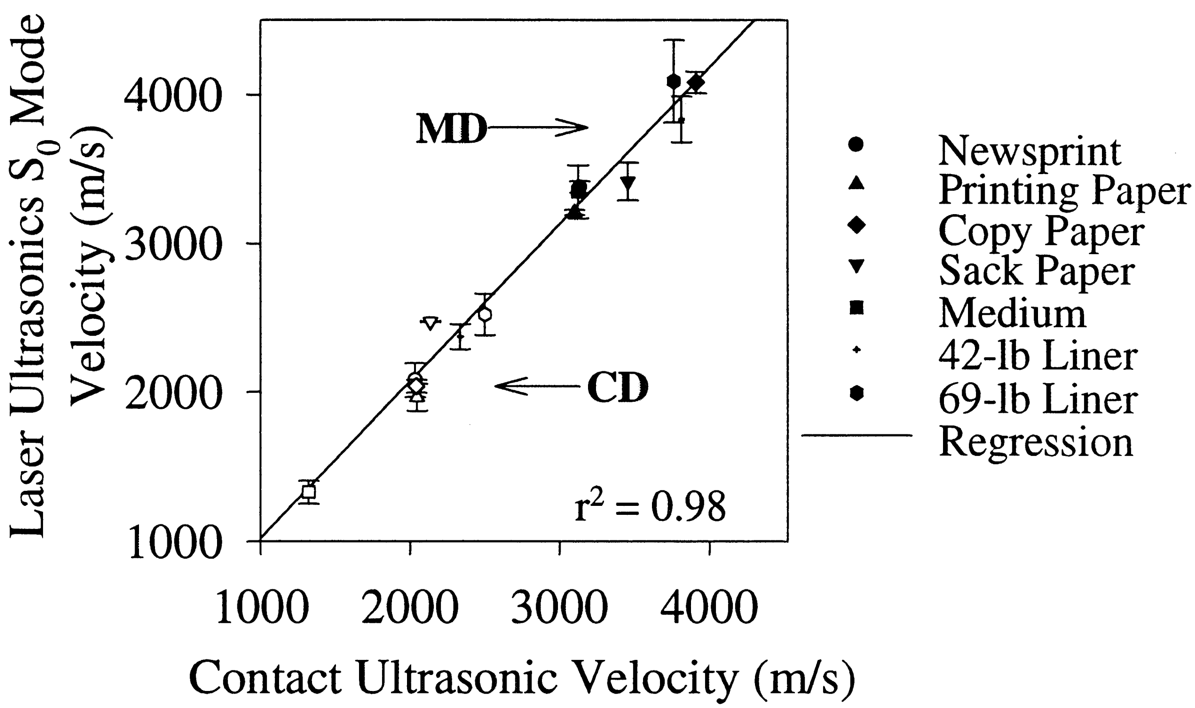

Fig. 8. Laser ultrasonics vs. contact ultrasonic velocity. MD and CD data points are located on the upper right and lower left corners of the plots, respectively.